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DEVELOPMENT OF A HYDROGEN-FUELED DIVER HEATER.(U)
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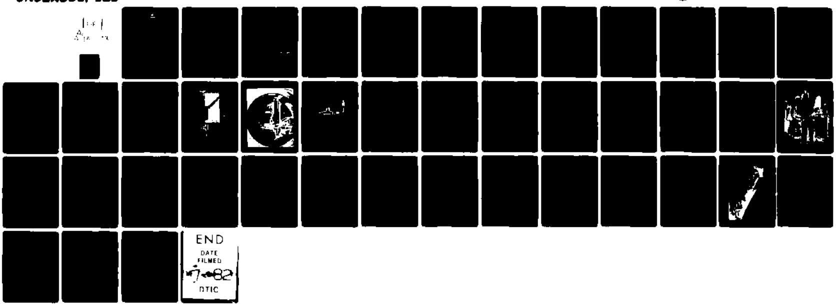

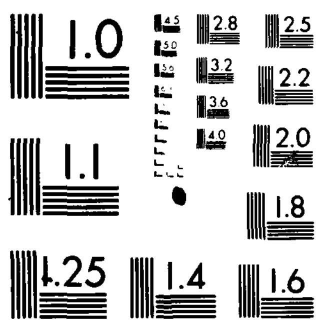

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Battelle
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Report

(1)

SUMMARY REPORT

on

DEVELOPMENT OF A HYDROGEN-FUELED DIVER HEATER

to

NAVAL COASTAL SYSTEMS CENTER

May 1982

by

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Contract No. N61331-81-C-0075

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ABSTRACT

In this research program breadboard heaters were developed which use the combustion of hydrogen in oxygen to heat a flow of water. Both a catalytic heater and a flame-burner were built and tested to an output level of 2 kW.

A gas-powered water pump was designed and built to provide water circulation.

FOREWORD

This report summarizes research conducted on the development of a hydrogen-fueled diver heater under Contract No. N61331-81-C-0075 from September 1981 to April 1982. The work was performed by the Battelle-Columbus Laboratories for the Naval Coastal Systems Center, with Mr. Maxwell W. Lippitt, Jr., serving as technical monitor. The principal investigator was Mr. Peter S. Riegel. Technician Gary E. Bates built the heaters and pump and assisted in their design.

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SUMMARY REPORT

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INTRODUCTION

This is the summary report of progress on the development of two hydrogen-fueled diver heaters. The heaters were developed by Battelle for the Naval Coastal Systems Center under Contract No. N61331-81-C-0075.

It is well known that the efficiency and safety of divers are impaired by the cold-water environment, and mission duration must sometimes be shortened because no way exists to keep the divers warm for a sufficiently long duration. In the Navy's Diver Thermal Protection program, this problem has been addressed, and considerable improvements in diver garb and equipment are being made.

In one development effort, the Navy acquired a number of propane-fueled catalytic heaters, which produce both thermal and electrical energy through the controlled combustion of the fuel gas. However, because of the unfavorably low evaporation pressure of liquid propane, coupled with the increasing ambient pressure of the water as depth increases, the propane heater is largely ineffective at depths greater than about 200 feet. Other gases of the hydrocarbon type also possess the limitation of low evaporation pressure.

However, if a gas can be supplied to a catalyst bed or combustion chamber in the presence of oxygen, it will burn, and one such gas that is eminently suited to the purpose may be hydrogen. Long ignored because of its well-known explosive properties, it can serve well as a fuel, as exemplified by its use as a rocket fuel. Of course, attention must be scrupulously paid to the safety aspects of its use in a diver-carried piece of gear. One advantage of the use of hydrogen in such an application is that its combustion product, when burned in an oxygen atmosphere, is water alone. No toxic gases will be produced. The potential of hydrogen for use in a diver heater is great.

SUMMARY

Two breadboard heaters have been built and tested, both of which employ the combustion of hydrogen in oxygen to produce heat. A water pump, driven by the expansion of the oxygen supply, has also been built to provide the heaters with cooling water.

The first heater was built in accordance with the original concept, which was to introduce hydrogen into a recirculating flow of oxygen, and to pass the resulting mixture over a catalyst bed. The catalyst causes the hydrogen to combine with the oxygen on the surface of the catalyst pellets, producing heat and steam. The steam is condensed by cooling with a water jacket, and the heat gained by the cooling water can be used to heat a diver.

A second heater was built which uses open-flame combustion of hydrogen in oxygen within a cooled copper tube. Again, the heat removed by the cooling water may be used to heat a diver.

The water pump consists of two linked oscillating cylinders. One cylinder, powered by partial expansion of the incoming oxygen flow, drives the other cylinder, which pumps water. Check valves provide unidirectional flow of the pumped water.

Tests show that both heaters are capable of providing 2 kW of thermal energy, which was the design goal. The open flame tube burner is considered to be the better of the two heaters because of superior characteristics of operation, simplicity of design, and ease of operation.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were reached during the course of research on heater and pump development:

(1) Thermoelectric power driving a small dynamic pump is not as attractive as using gas power to do the same thing.

(2) Catalytic reaction of hydrogen within a recirculating flow of oxygen is possible at the pressures required (up to 450 FSW) but operation is undesirably complex and occasionally unpredictable.

(3) Direct combustion of an oxy-hydrogen flame can provide the required heat at the target depth with a minimum of complexity, both of design and operation.

It is therefore recommended that:

(1) Further development of the direct-combustion heater in combination with the gas-powered pump be undertaken. While single, diver-carried heaters may present unacceptable operational or psychological barriers, the direct-combustion heater has great potential for use in areas where a fixed unit might be desirable, such as in a swimmer delivery vehicle or a PTC. A single, simple heater could provide all of the heat needed to keep all of the passengers warm with only a small increase in vehicle payload.

RESEARCH ACTIVITY

The first step in the research was to determine the amounts of gas required to produce the required heat of 2 kW. Hydrogen has a higher heating value (HHV) of 319 B/lb, and a lower heating value (LHV) of 270 B/lb. The difference between HHV and LHV is the energy of water condensation. For an output of 2 kW (114 B/min), a flow of .42 scfm of hydrogen is required, based on the LHV. Since two volumes of hydrogen requires only one volume of oxygen, to combine stoichiometrically, a flow of .21 scfm of oxygen is thus required. The reaction of the two, at the stated rates, will produce water at the rate of 32 cubic inches (about 1 pint) per hour.

Catalytic Heater

Reaction of a hydrogen flow introduced directly into a catalyst bed through a porous tube was considered, but calculation showed that a very high temperature would occur at the pellet surface, enough to destroy the precious-metal reaction surface. Therefore, the approach was not considered further. Instead, it was concluded that the hydrogen-oxygen would have to be premixed in some manner so that a low concentration of hydrogen would encounter the bed, keeping temperatures reasonable.

Recirculation

If a small amount of excess oxygen is provided, it is theoretically possible to recirculate the excess in such a way that the net flow to the bed is mostly oxygen, with only a small amount of hydrogen present. Recirculating with the oxygen, of course, would be an amount of uncondensed steam produced by the reaction. A small vent would allow the condensate, as well as the small amount of excess oxygen, to leave the system.

Sufficient recirculation must be provided so that the stream enters the bed at a low hydrogen concentration, so that the mixture will not detonate. Also, a low hydrogen concentration will keep bed temperature low, because the excess oxygen in the mixture will absorb much of the heat generated at the catalyst surface. Recirculation on the order of 15 to 20 parts recirculated to each part added would keep hydrogen levels to less than 5 to 7 percent, well below the detonation limit in oxygen. Although this level would be flammable, a low bed temperature would keep the mixture at a temperature below that required for autoignition.

Jet Pump Recirculation. After considering ways in which the recirculation could be driven around the loop, it seemed that a jet pump, or ejector, showed the greatest promise. It has no moving parts and uses the energy in the incoming gas to impart flow energy to the recirculated stream of gas.

The amount of oxygen required for operation, as well as the amount of recirculation required, were very close to those required in a previous Navy task, in which Battelle used an air ejector to provide recirculation in a semi-closed circuit atmosphere control system used in a portable recompression chamber.

Because of this similarity, it was decided to build an ejector similar to that in the portable recompression system. That ejector uses a .008 inch primary nozzle operating at 500 psi, driving air into a 3/8inch secondary nozzle, and achieving about 24 to 1 recirculation. We built three primary nozzles, of .006, .008 and .010 inch diameter mounted in the end of an oxyacetylene welding tip.

Three secondary throats were also built, of 7/16, 3/8, and 1/2 inch diameter. It was felt that with the potential combinations available, one would be found to fit the requirement.

Preliminary calculation of heat flow led us to the conclusion that a catalytic reactor having about 1 square foot of condensation area would be required. A 6 x 12 inch reactor case was built of sandwich construction with cooling on the two major sides. Into this case were fitted primary jet, secondary jet, and catalyst bed (Figure 1). Before insertion of the catalyst bed, a calibrated flow orifice was made so that the amount of recirculation developed by the various primary/secondary jet combinations could be determined. Results of the recirculation tests are shown in Figure 2. With the capacities of the various nozzle combinations established, it was decided to employ the .006-inch primary nozzle with the 1/2-inch secondary nozzle, achieving about 17 to 20 to 1 recirculation at atmospheric pressure. The actual amount of recirculation under pressure was not known, but it is known that in similar systems the recirculation increases with pressure.

Preliminary Testing and Debugging

A preliminary heating test was done at atmospheric pressure, to gain an initial feel for the apparatus. Because preliminary results were encouraging, the heater was installed in a pressure chamber for a hyperbaric run. The hyperbaric runs were extremely discouraging, and we were

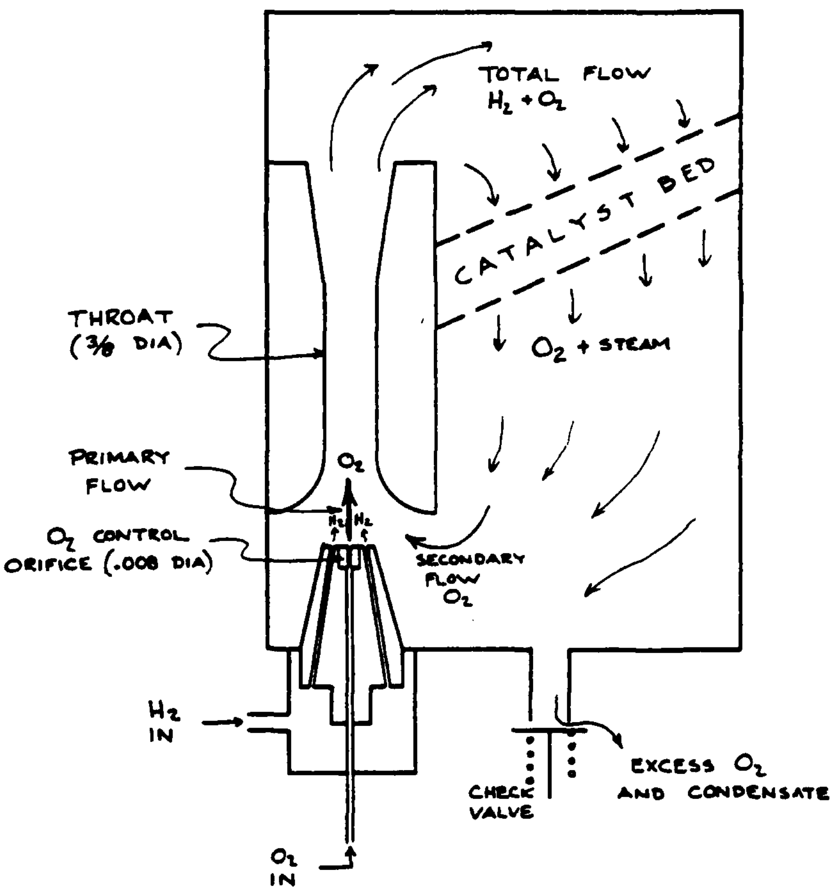


FIGURE 1. CATALYTIC BURNER-SCHEMATIC

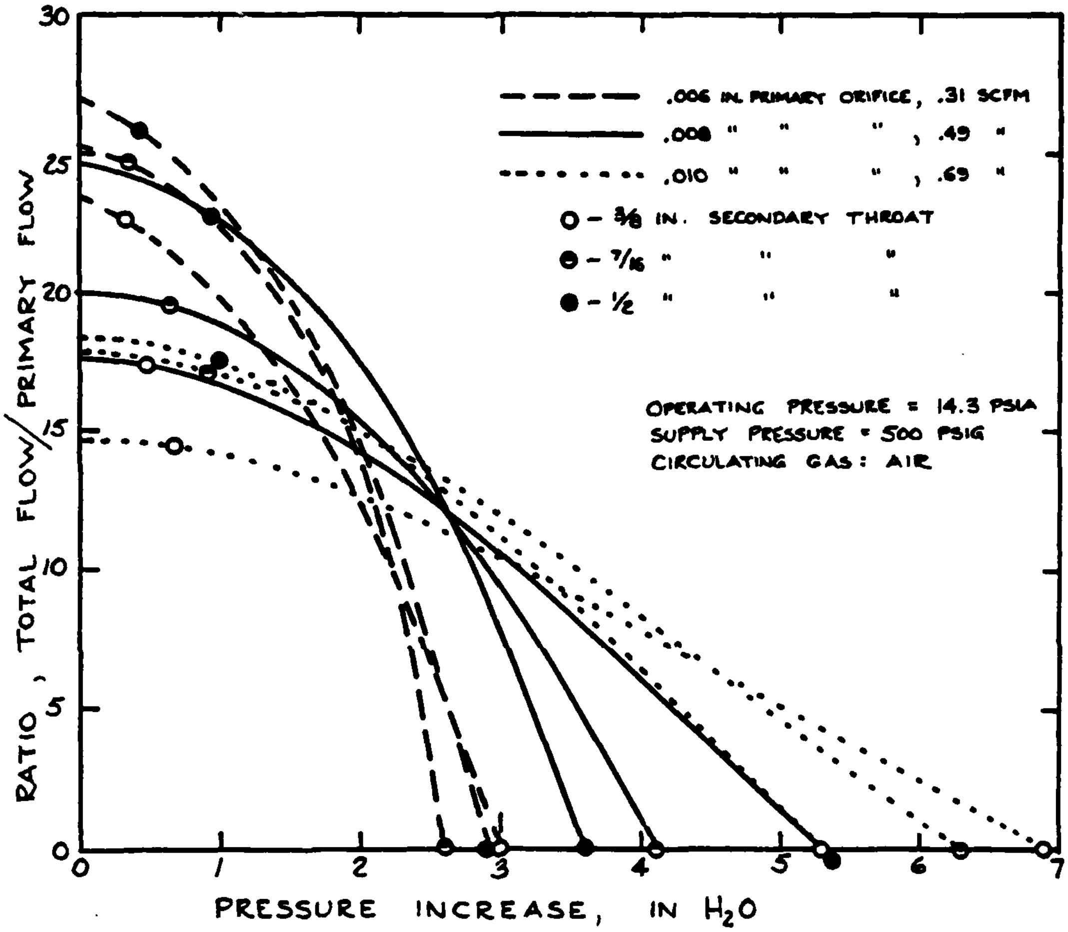


FIGURE 2. RECIRCULATION PERFORMANCE OF CATALYTIC HEATER EJECTOR CONFIGURATIONS

unable to attain any operation beyond 60 psig. Problems at this point were:

(1) Unit started very slowly, and took minutes to reach a steady operating temperature.

(2) Once used, the unit would not restart. We suspected damage to the catalyst (palladium coating on 1/8-inch alumina pellets).

(3) At elevated temperatures, reaction would leave the bed and transfer to the injector tip, where the hydrogen and oxygen would burn. Once this started, it could not be stopped except by shutting off the hydrogen flow.

(4) The .006-inch primary nozzle required too much oxygen pressure to produce the desired heat output.

After trying in various ways to make the catalytic heater work, we found that if we let the combustion occur at the tip, heat was nicely produced. Hydrogen could be introduced just about anywhere in the reactor and burned with no apparent ill effects. However, the extreme turbulence introduced into the reactor by the action of the jet pump caused the flame to be rather widely distributed about the inside of the reactor, judging from observed variations in temperature and internal discoloration of the cooling jacket. Still, when the hydrogen was allowed to burn, the heater worked better than when it was operated catalytically. Because of this, a special heater was made that was designed as an open-flame combustor. It will be discussed subsequently.

Experimentation with primary and secondary nozzles led to the adoption of a heater using the .008-inch primary nozzle in a 3/8" secondary throat in future testing, which reduced required oxygen pressure. When the catalytic burner was operated at elevated pressures, operation was poor, as mentioned. One phenomenon that we noticed, when the chamber was opened after a run, was that there was tarnished brass, greenish water produced, and a smell of nitric acid. This observation led us to the belated conclusion that perhaps the catalytic reactor was ingesting nitrogen from the chamber atmosphere (the chamber was pressurized and continuously ventilated with nitrogen during hyperbaric runs). Accordingly, a check valve was fitted to the exhaust tube of the reactor and the experiments repeated. Final configuration is shown in Figures 3 through 6.

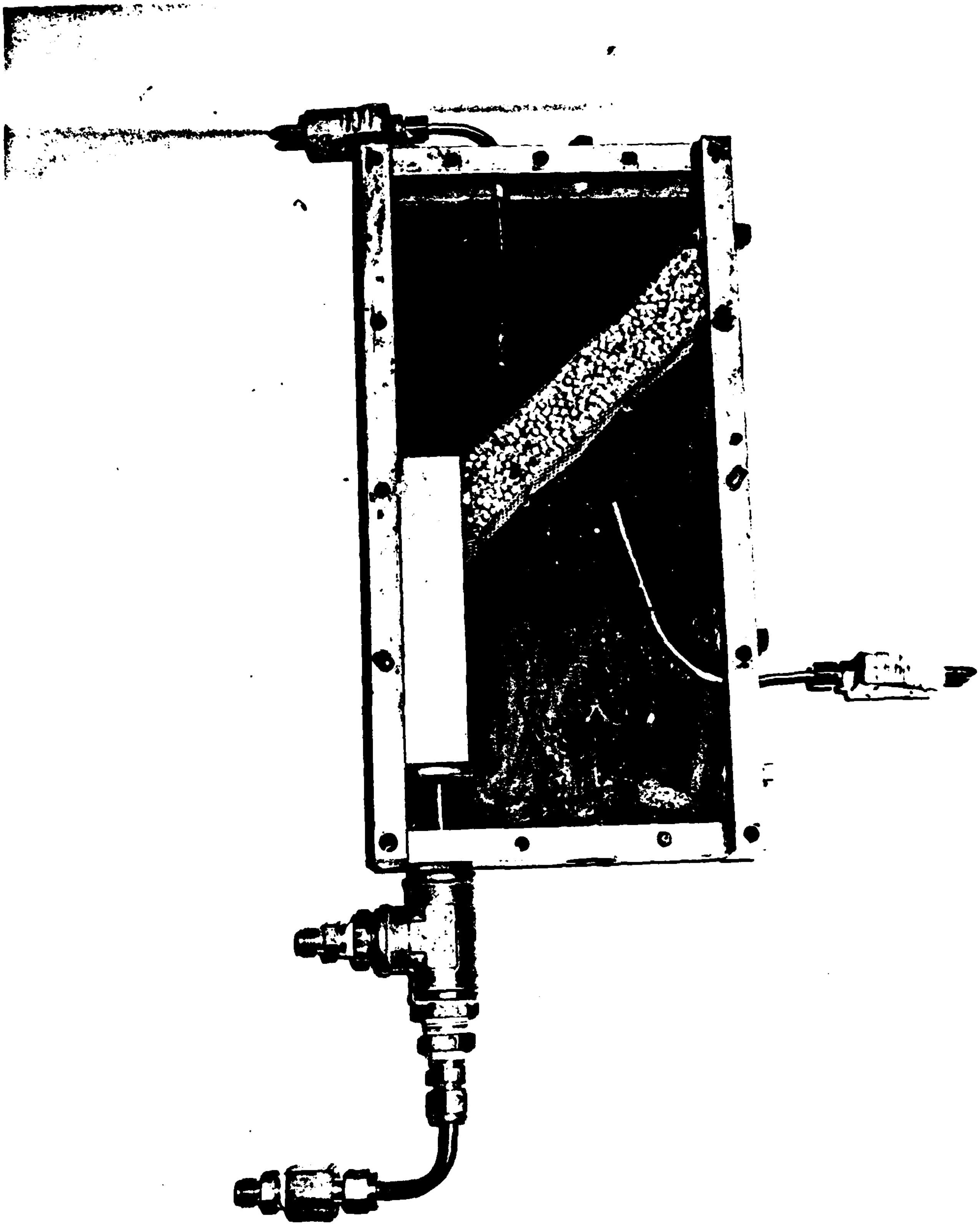


FIGURE 3. CATALYTIC HEATER INTERIOR

Note: Thermocouples for measurement of gas temperatures on both sides of catalyst bed.

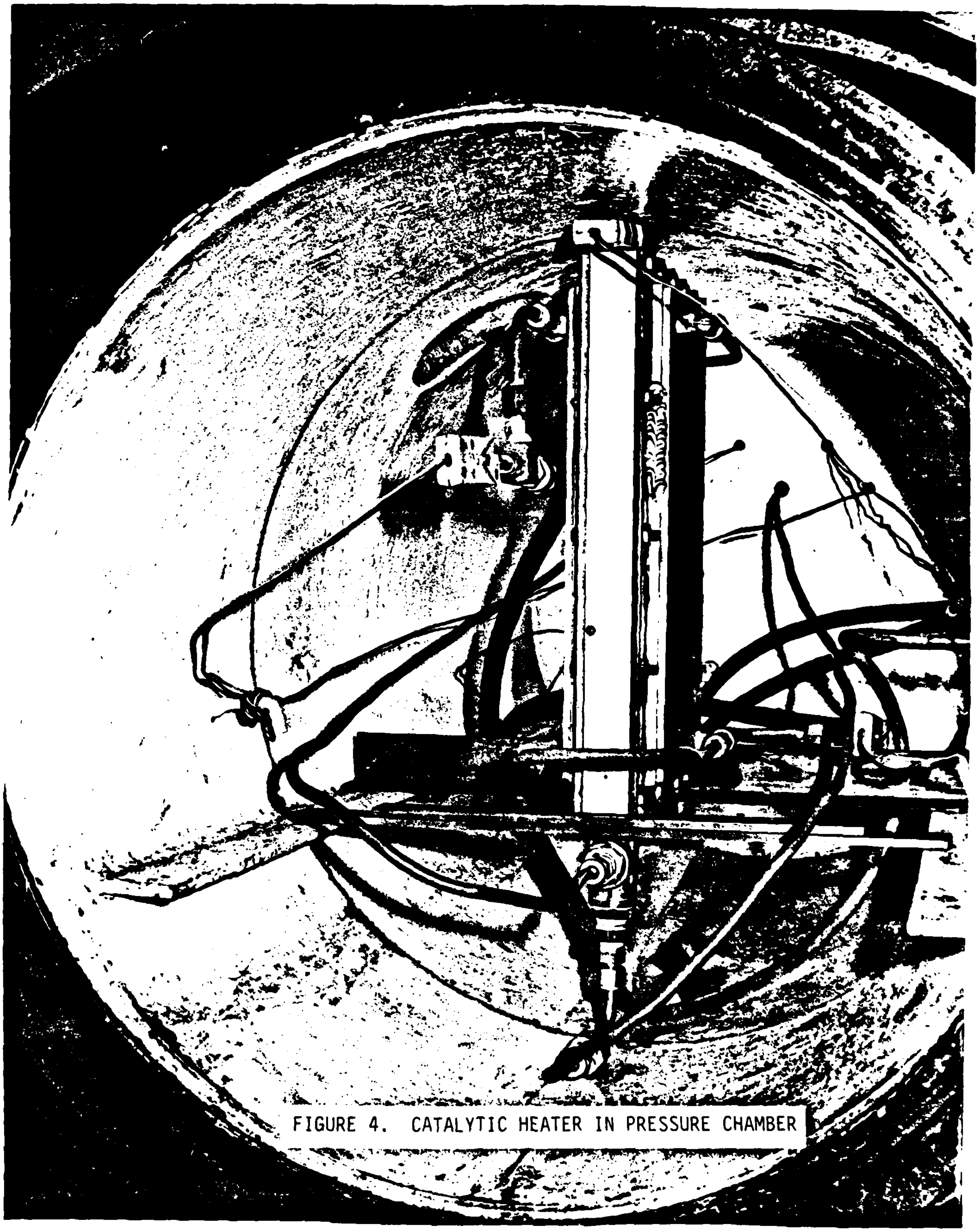


FIGURE 4. CATALYTIC HEATER IN PRESSURE CHAMBER

Note water jackets on both sides of heater.

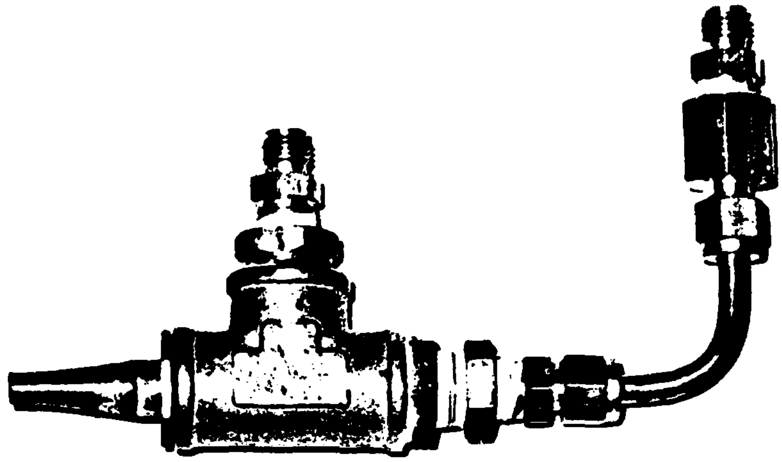
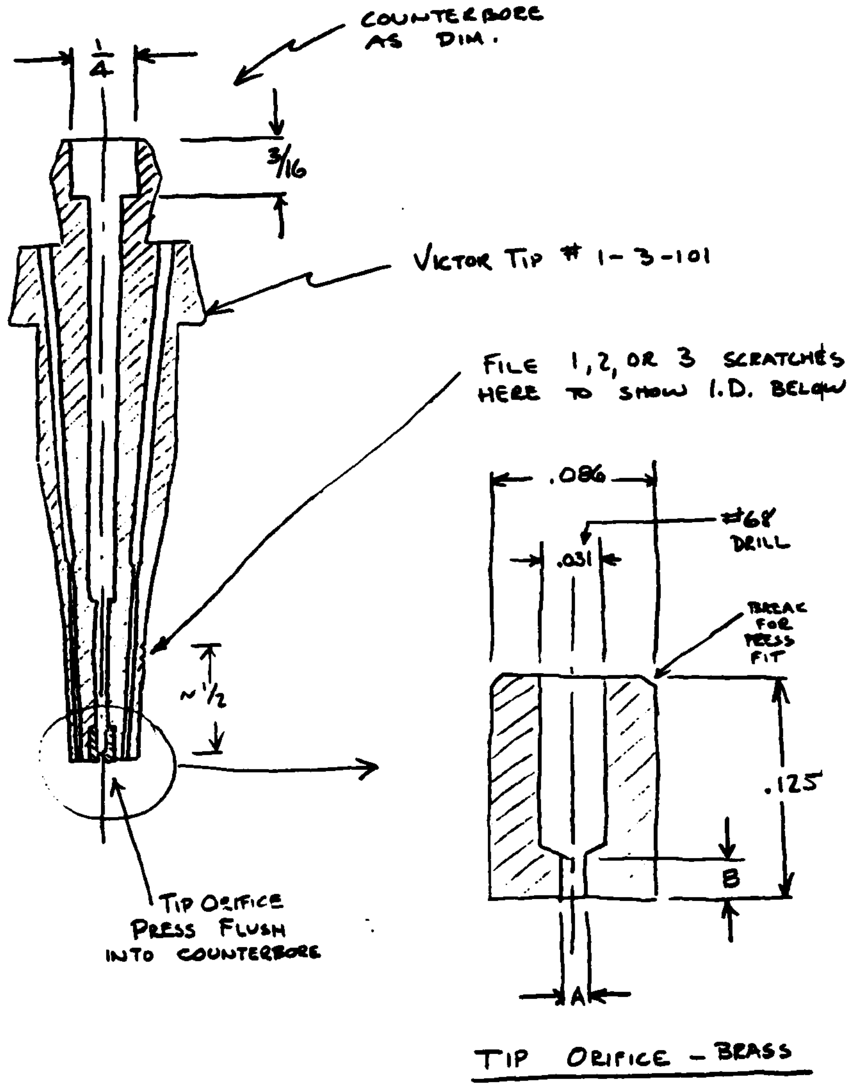


FIGURE 5. GAS INJECTOR

MIXING TIP



NOTE - 0.008" ORIFICE WAS USED IN FINAL CATALYTIC BURNER

I.D.	A	B	No REQ'D
1	.006	.020	1
2	.008	.025	1
3	.010	.030	1

FIGURE 6. MIXING TIP

Final Hyperbaric Tests of Catalytic Heater

After the check valve was fitted, the catalytic reactor's operation was much improved, and we were able to obtain data all the way to the 450 FSW pressure desired. Results of these tests may be seen in Figures 7 and 8 and Table 1.

Idiosyncracies of the Catalytic Heater

Operation of the catalytic reactor was erratic. Once the reactor was shut down, it would not reignite. Restarting was made possible when the cooling water was shut off and the casing of the reactor heated with a torch to about 110 to 125 F, judging by touch. At that point the reactor would respond to the introduction of hydrogen with a heat output.

At elevated pressure and low hydrogen flows, a sharp temperature drop was sometimes observed. The drop could be reversed by increasing hydrogen flow, if done in time. If we waited too long, the reactor would die and fail to reignite. Under pressure in the chamber it could not be heated by external means, so the chamber would have to be dumped and the door opened to allow reheat for starting. Still, there was a reasonably wide range of operation that was reasonably reliable.

Startup required care. Normal procedure was to turn on the oxygen to its operating level, and allow a few minutes to pass to purge the interior of nitrogen. Then a very small flow of hydrogen was introduced, to keep the mixture below the 4 percent ignition level. After a few minutes the interior temperature would begin to rise, and as it did so the flow of hydrogen was gradually increased. If hydrogen flow was increased too fast, the unit would sometimes respond with a loud report, which sounded much like the discharge of a smallbore rifle. However, once we become familiar with the unit, we learned how to turn it on without internal explosions.

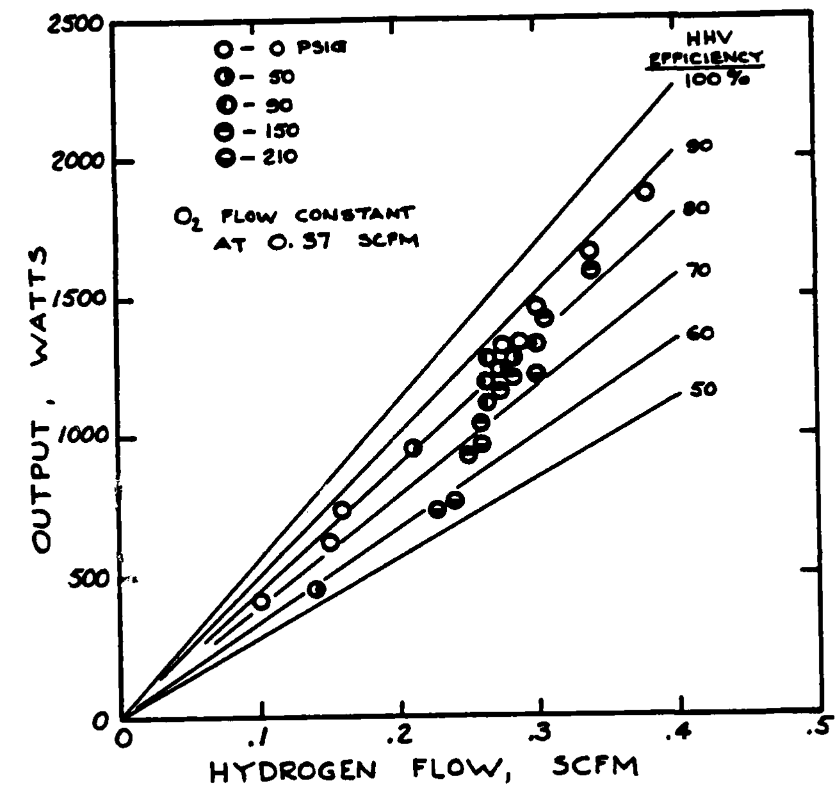


FIGURE 7. HEAT OUTPUT VS HYDROGEN FLOW FOR CATALYTIC BURNER AT VARIOUS OPERATING PRESSURES

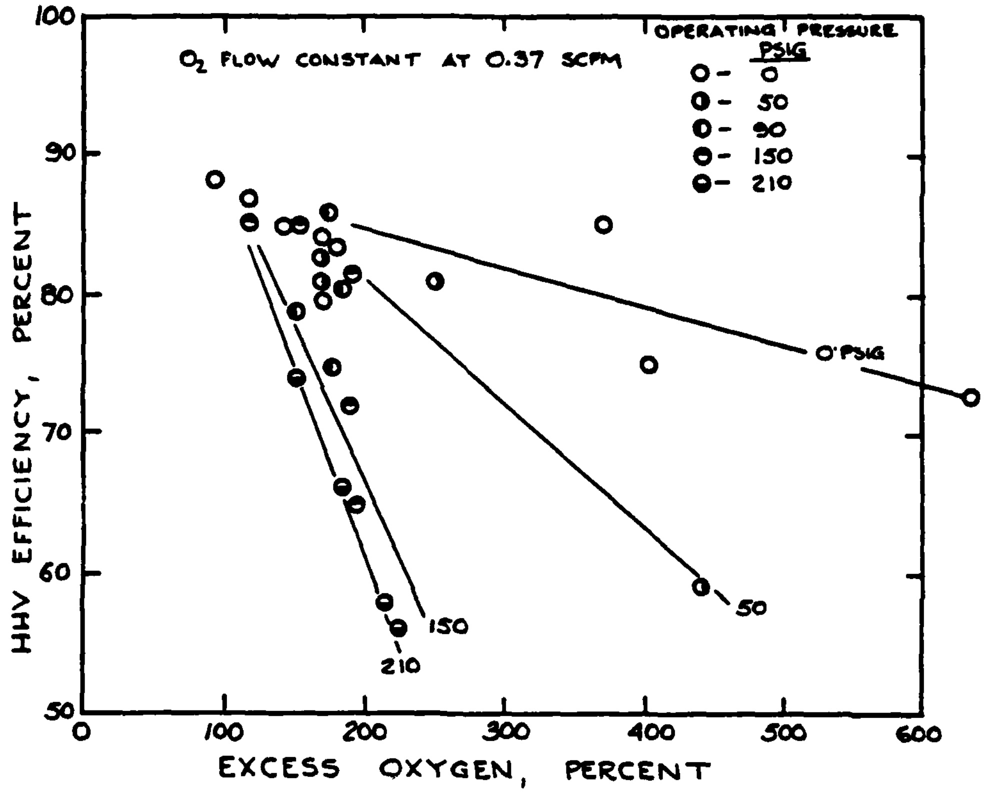


FIGURE 8. EFFICIENCY VS EXCESS OXYGEN FOR CATALYTIC BURNER AT VARIOUS OPERATING PRESSURES

Table 1. Catalytic Burner Test Data

RUN NUMBER	O2 FLOW SCFM	H2 FLOW SCFM	H2O FLOW GPM	DELTA T DEG F	P CHAMBER PSIG	HEAT OUTPUT WATTS	COMBUSTION EFF, PCT	EXCESS O2 PERCENT	GAS TEMP TO BED, F	GAS TEMP FROM BED, F
1	.373	.278	.395	22	50	1274	81.6	169	222	495
2	.373	.278	.392	22	60	1265	81.1	169	224	491
3	.373	.278	.382	23	75	1287	82.5	169	222	474
4	.373	.268	.366	21	90	1126	74.7	178	206	447
5	.373	.298	.376	24	90	1324	79.1	151	186	467
6	.373	.278	.382	23	50	1287	82.5	169	174	502
7	.373	.213	.387	17	50	964	80.7	251	159	440
8	.373	.138	.387	8	50	454	58.5	440	114	297
9	.373	.148	.422	10	0	618	74.5	405	149	449
10	.373	.278	.427	21	0	1314	84.2	169	247	669
11	.373	.278	.448	21	30	1380	88.4	169	198	512
12	.373	.278	.44	21	61	1355	86.9	169	198	475
13	.373	.265	.435	19	91	1211	81.3	181	190	426
14	.373	.26	.422	17	142	1051	71.9	187	153	408
15	.373	.299	.422	20	211	1236	73.7	150	168	417
16	.373	.263	.416	16	208	976	66.2	184	151	385
17	.373	.233	.422	12	210	742	56.7	221	126	340
18	.373	.237	.408	13	215	778	58.5	215	123	327
19	.373	.269	.467	19	90	1301	86.1	177	151	433
20	.373	.265	.456	18	140	1204	80.8	181	153	422
21	.373	.273	.462	18	150	1218	79.6	174	155	412
22	.373	.295	.459	21	155	1413	85.4	153	164	458
23	.373	.342	.462	24	149	1624	84.7	119	177	493
24	.373	.253	.448	14	145	920	64.9	196	143	296
25	.373	.278	.472	19	0	1315	84.3	169	126	636
26	.373	.157	.467	11	0	753	85.4	375	103	447
27	.373	.101	.472	6	0	415	73	637	84	343
28	.373	.306	.47	21	0	1446	84.2	144	131	673
29	.373	.343	.475	24	0	1671	86.8	118	135	730
30	.373	.38	.475	27	0	1880	88.1	96	140	775

Once up to operating temperature, the reactor heated without incident, and the flow of hydrogen could be safely varied and the heat output easily controlled.

Reliable operation was attained when internal temperature was maintained below 700 F, as measured by a thermocouple located just downstream of the bed (see Figure 3 for thermocouple location). Although we deliberately provoked backfires and ignition of the gas at the tip at atmospheric pressure, we avoided doing so under any condition when the chamber was under pressure, because we feared an explosion. Therefore, we did not obtain hyperbaric data regarding the ultimate output of the unit at elevated internal temperatures. Since any heater to be developed will not operate at those elevated temperatures, this lack of data should not represent a serious loss.

Tube Burner

Observation of the catalytic burner under flame combustion conditions, combined with dissatisfaction with its performance under catalytic operation, led us to seek another way to extract the heat from the hydrogen. Flame burning, we thought, if it could be controlled, might represent a reasonable approach to the problem. Since there would be no catalyst present, flame temperatures could be allowed to be as high as they might get, just so they were kept away from vulnerable parts of the apparatus.

Use of the welders tip in the catalytic bed led us to try the same approach in a "tube burner". A double-walled tube was constructed of 1-1/4-inch and 2-inch copper tubing. One end was fitted with a check valve, and the other end contained a welder tip, directed straight down the central axis. Oxygen was fed into the central hole of the tip, and hydrogen into the six peripheral holes. Water was circulated through the space between the two copper pipes. Figures 9, 10 and 11 show the tube burner configuration.

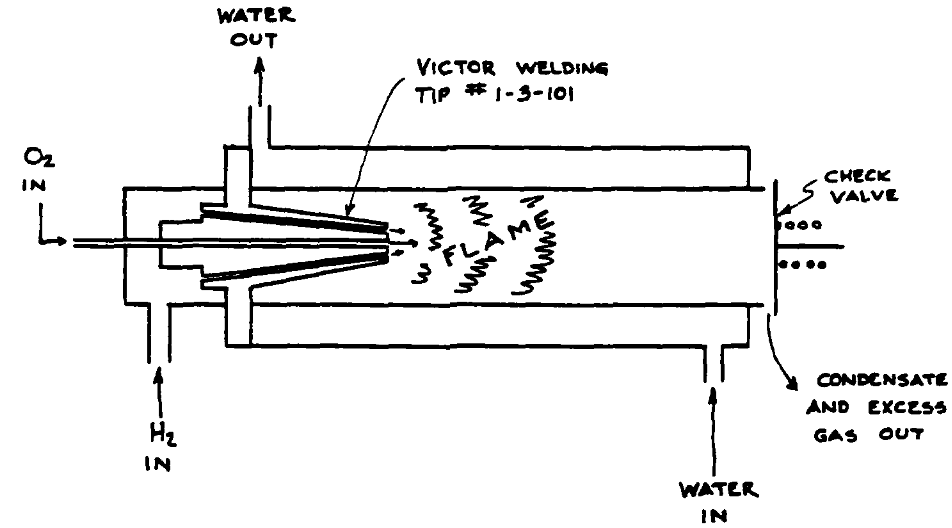


FIGURE 9. TUBE BURNER-SCHEMATIC

FIGURE 10. TECHNICIAN HOLDING TUBE BURNER

Operation

The unit was tested in a slightly inclined position, discharge low, to permit condensate to run out by gravity. Water was fed in at the gas discharge end, and out at the inlet end, at the high point of the water jacket, to remove any air bubbles that might get into the system and assure that the central tube never lost contact with cooling water at any point.

Water was turned on at a predetermined flow rate, and the desired oxygen flow established. After a few seconds had elapsed, the hydrogen was turned on at a low rate and ignited at the open end with a match. Flame transferred smoothly and swiftly up the tube and established a permanent location at the outlet of the welder tip. At this time the hydrogen flow was increased to the levels desired for testing. Unlike the catalytic burner, the tube burner was not temperamental. It operated equally well with excess oxygen or excess hydrogen, and flaming did not occur at the discharge end unless it was deliberately ignited to burn off the excess hydrogen, as was sometimes done to reduce the danger of hydrogen discharging freely into the room. Normally operation occurred with a fixed flow of oxygen sufficient to burn the greatest amount of hydrogen required to produce the heat level desired, and hydrogen flow was varied to obtain the specific output desired.

Testing

Once we had satisfied ourselves, by testing at atmospheric pressure, that the unit was tame, we tested it under pressure in a chamber to the 450 FSW level. Results of testing may be seen in Figures 12 through 16 and Tables 2 and 3.

When we built the burner no great attention was paid to its dimensions, since the investigation was considered preliminary. However, it appears that the unit is somewhat oversize as presently constructed. At atmospheric pressure we turned the burner to an output of about 2200 watts and gradually inserted a shielded thermocouple. No significant temperature rise was noted in the interior until a distance of about

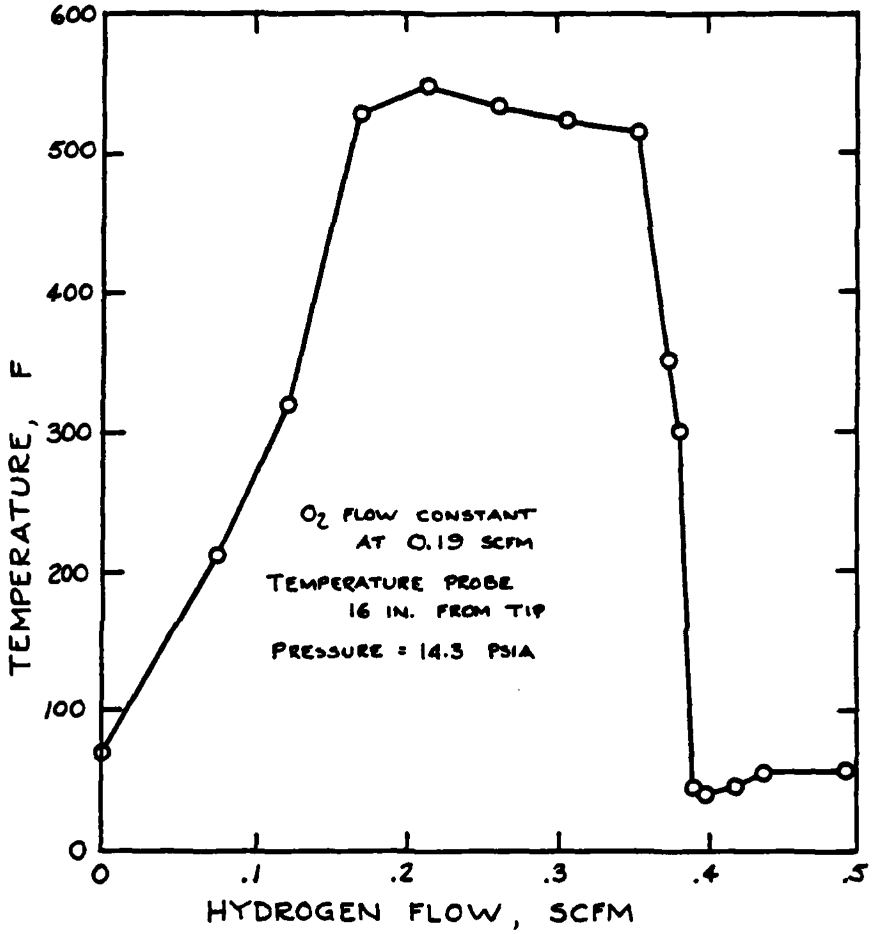


FIGURE 12. TEMPERATURE VS HYDROGEN FLOW FOR TUBE BURNER AT 14.3 PSIA

Note the sharp drop in temperature as hydrogen flow approaches the stoichiometric level of .38 scfm. At this point all the incoming gas is consumed, and no net flow of excess O_2 or H_2 is available to carry heat down the tube.

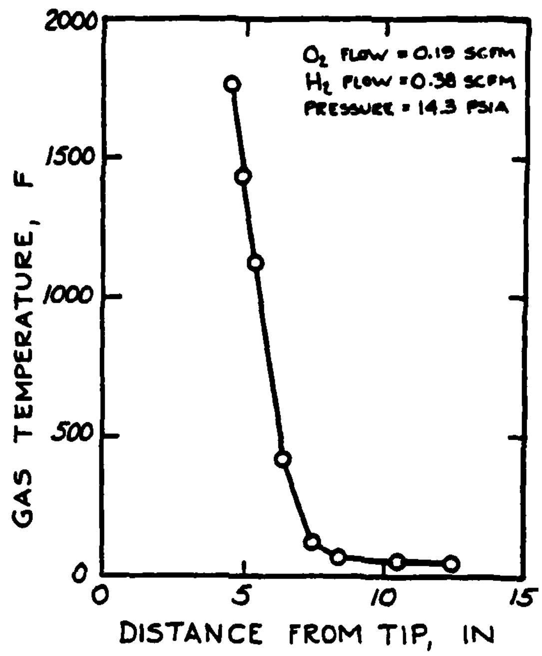


FIGURE 13. GAS TEMPERATURE VS DISTANCE FROM TIP FOR TUBE BURNER AT 14.3 PSIA

Note: This test was performed at stoichiometric condition at an output level of 2250 watts.

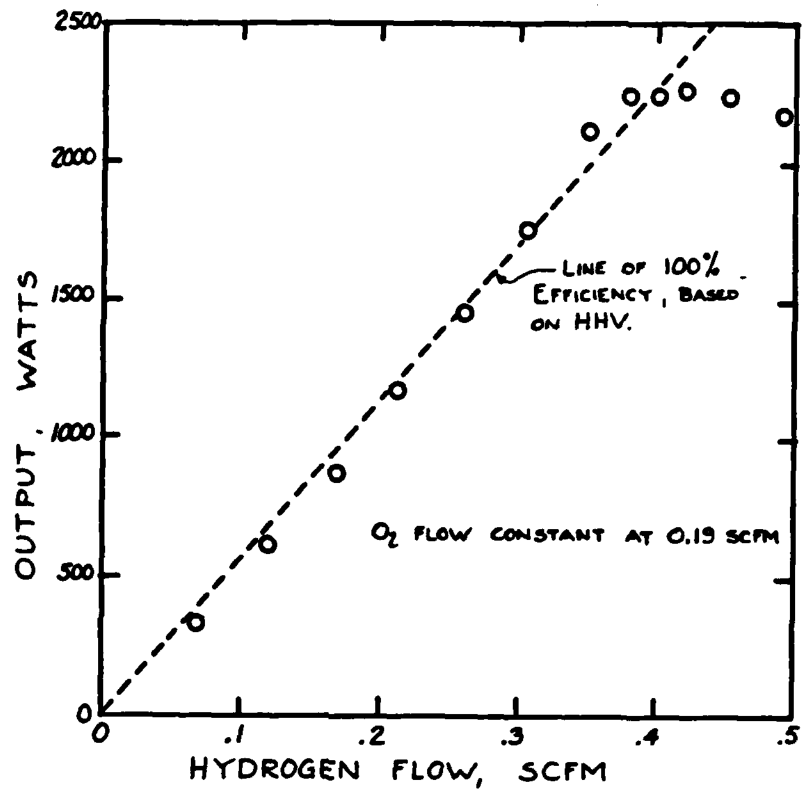


FIGURE 14. HEAT OUTPUT VS HYDROGEN FLOW FOR TUBE BURNER

Note: Excess hydrogen flow above stoichiometric level produces no further increase in heat output, since no oxygen is available for its combustion.

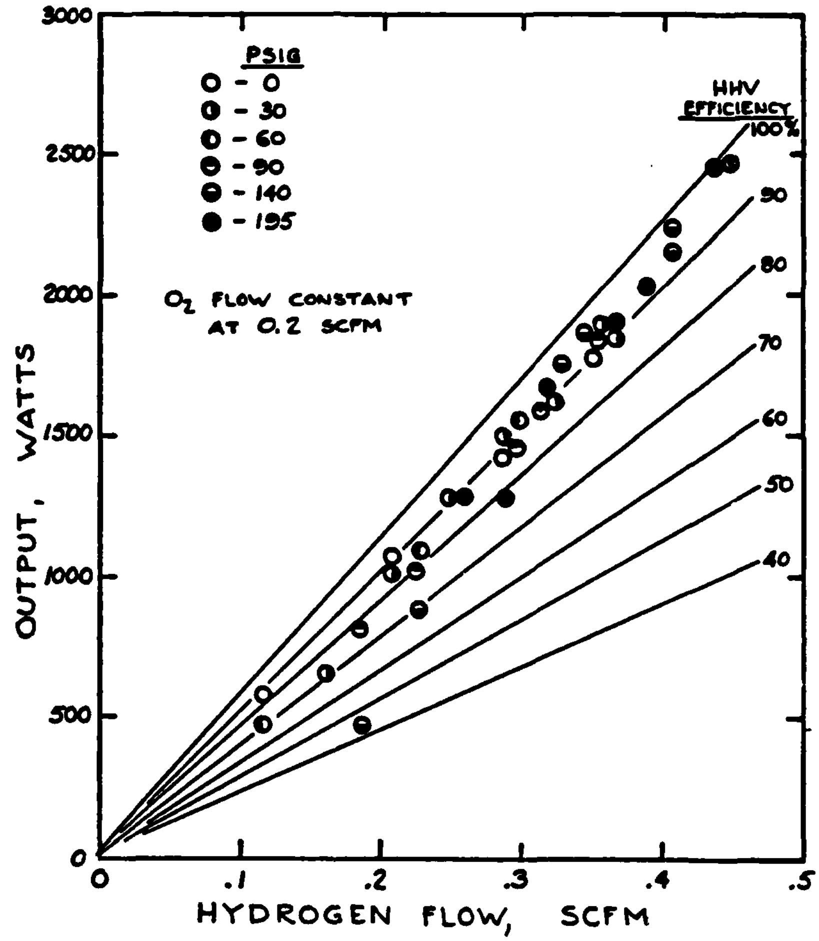


FIGURE 15. HEAT OUTPUT VS HYDROGEN FLOW FOR TUBE BURNER AT VARIOUS OPERATING PRESSURES

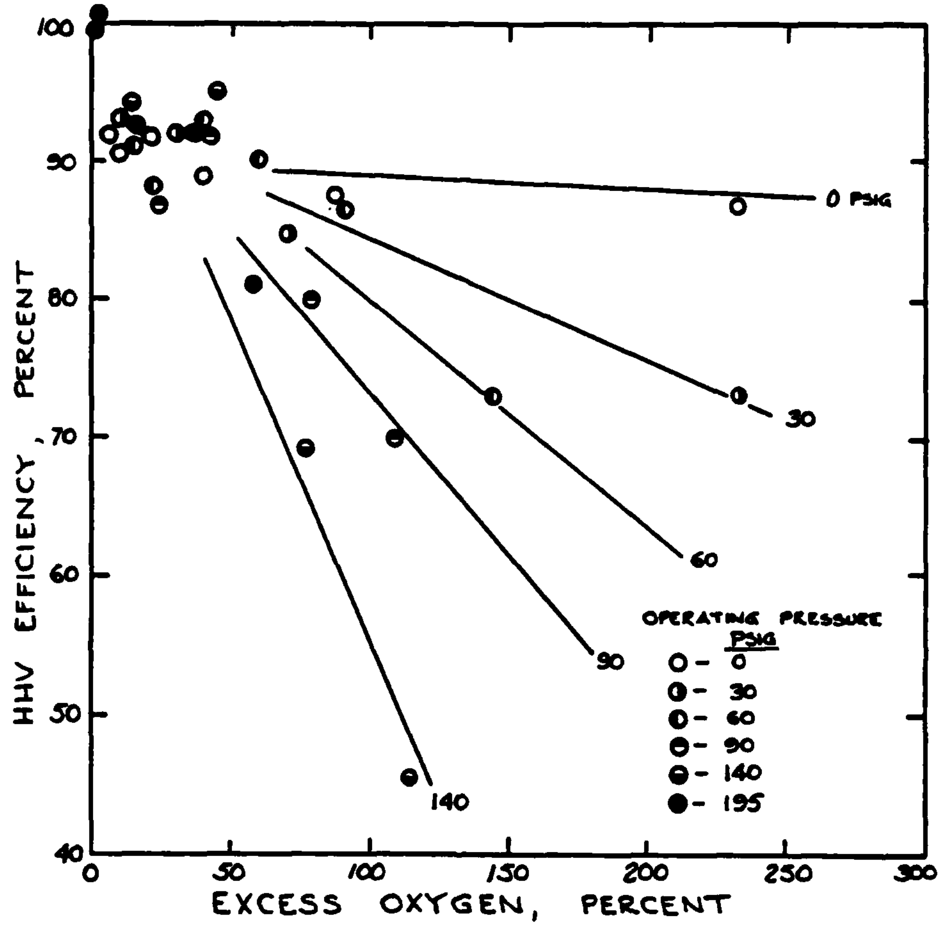


FIGURE 16. EFFICIENCY VS EXCESS OXYGEN FOR TUBE BURNER AT VARIOUS OPERATING PRESSURES

Table 2. Tube Burner Test Data

RUN NUMBER	O2 FLOW SCFM	H2 FLOW SCFM	H2O FLOW GPM	DELTA T DEG F	P CHAMBER PSIG	HEAT OUTPUT WATTS	COMBUSTION EFF, PCT	EXCESS O2 PERCENT
1	.198	.36	.475	27	0	1880	92.6	10
2	.198	.36	.472	28	30	1939	95.5	10
3	.198	.36	.462	30	60	2030	100	10
4	.198	.36	.443	29	75	1883	92.8	10
5	.198	.36	.435	29	90	1849	91.1	10
6	.198	.323	.435	25	90	1594	87.5	23
7	.198	.286	.435	23	90	1467	92.2	41
8	.198	.226	.43	16	90	1008	80.7	79
9	.198	.194	.422	13	90	803	75.2	109
10	.198	.36	.435	30	90	1913	94.2	10
11	.198	.36	.435	30	75	1913	94.2	10
12	.198	.36	.435	29	60	1849	91.1	10
13	.198	.323	.422	26	60	1607	88.2	23
14	.198	.286	.408	25	60	1496	92.8	39
15	.198	.248	.414	21	60	1273	90.7	59
16	.198	.211	.408	17	60	1017	85.1	87
17	.198	.164	.414	11	60	667	72.8	144
18	.198	.36	.414	31	60	1880	92.6	10
19	.198	.36	.422	30	45	1854	91.3	10
20	.198	.36	.416	31	30	1892	93.2	10
21	.198	.304	.414	26	30	1576	91.8	30
22	.198	.23	.416	18	30	1098	84.5	72
23	.198	.118	.422	8	30	494	73.4	232
24	.198	.36	.422	30	30	1854	91.3	10
25	.198	.36	.419	31	15	1904	93.8	10
26	.198	.36	.422	30	0	1854	91.3	10
27	.198	.286	.408	24	0	1436	89.1	39
28	.198	.211	.422	17	0	1051	87.9	87
29	.198	.118	.448	9	0	591	87.8	232
30	.198	.081	.448	6	0	394	84.9	381
31	.198	.36	.456	28	0	1873	92.2	10

Table 3. Tube Burner Test Data

RUN NUMBER	O2 FLOW SCFM	H2 FLOW SCFM	H2O FLOW GPM	DELTA T DEG F	P CHAMBER PSIG	HEAT OUTPUT WATTS	COMBUSTION EFF,PCT	EXCESS O2 PERCENT
1	.199	.368	.422	30	107	1854	89.8	8
2	.199	.35	.419	30	140	1842	93.8	14
3	.203	.414	.422	35	140	2163	93	-2
4	.201	.364	.422	32	163	1978	96.9	10
5	.22	.424	.414	38	169	2304	96.8	4
6	.198	.358	.414	31	196	1880	93.4	11
7	.225	.445	.414	41	193	2486	99.5	1
8	.222	.39	.419	33	197	2027	92.5	14
9	.223	.323	.422	27	196	1669	92.2	38
10	.223	.285	.419	21	196	1290	80.8	57
11	.223	.439	.422	40	196	2472	100.4	2
12	.222	.43	.416	35	166	2136	88.5	3
13	.203	.418	.422	36	138	2225	94.8	-3
14	.203	.329	.414	29	141	1758	95.2	24
15	.203	.23	.408	15	140	898	69.6	77
16	.203	.191	.414	8	140	485	45.2	113
17	.203	.414	.414	37	140	2243	96.5	-2
18	.199	.392	.419	32	111	1965	89.4	2
19	.199	.362	.414	30	90	1819	89.6	10
20	.199	.362	.416	30	61	1831	90.2	10
21	.199	.362	.427	29	28	1815	89.4	10
22	.199	.362	.419	31	0	1904	93.8	10

8 inches from the burner tip was reached. At 4 to 5 inches from the tip the internal temperature measured nearly 2000 F. Further insertion produced a maximum temperature of 2555 F at which point the thermocouple burned up. From this we conclude that the entire burner could be about 18 inches long, rather than the present 27 inches. As can be seen from Figure 12, use of excess O_2 tends to carry heat farther down the tube than when operation is near a stoichiometric level. Nevertheless, the major heat transfer area lies within a foot of the nozzle. How hot does it get inside the burner? A maximum flame temperature of nearly 4000 F is attainable when burning hydrogen in air. In oxygen the temperature is likely far higher. Thermodynamic calculation, ignoring dissociation, indicates a maximum near 10000 F, although in reality the flame is probably not that hot.

Burner Wall Temperatures

No burner wall temperatures were measured. However, if it is assumed that all of the heat is transferred through the .050 tube wall to the water in the first 5 inches of tube length, a difference of only 5 F across the copper will pass 2000 watts. However, what of the water on the other side? Does it boil? In the tests, the output temperature never exceeded 100 F. There was no sound of boiling when an ear was put to the water jacket. If a film coefficient for water on the tube surface is taken at 1000 B/hr-ft^2-F, a temperature difference of 250 F is calculated between tube surface and water, which might cause local nucleate boiling. If nucleate boiling is calculated, a temperature difference of 85 F between tube surface and water is found. This, of course, assumes that a thin film of steam exists between tube and surrounding water. Neither of these calculations is particularly satisfying, the first because it predicts boiling when none was heard and the second because it leads to a value of about 170 F for the outer tube surface, which is not hot enough to boil water. Perhaps the assumption of a 5-inch-length for heat transfer is low; certainly if a longer length is assumed lower temperature differences will result.

Observation and calculation lead to the conclusion that little or no boiling is occurring, and that the temperature of the inner copper tube is less than 300 F, a safe level. If salt water is used for cooling, some fouling may be expected, which must be coped with by proper design of future units.

Water Pumping

At the start of the task it was planned to use an electrically-driven gear pump to circulate the water at a rate of 1 gpm. The power for the pump was to be provided from thermoelectric elements located on the heater, which utilize temperature difference between heater surface and ambient to generate electricity.

The more this approach was studied, the worse it looked. Although none of the potential problem areas presented insuperable obstacles, collectively they added up to an overly complicated way to pump a modest amount of water. Some drawbacks to the method were:

(1) Small, high speed pumps will cavitate and are hard to prime.

(2) Small DC motors are not available for continuous duty at the low power level required.

(3) Variation in heat output from the heater, required for keeping the diver comfortable, might adversely affect the operation of the thermoelectric generation.

Fortunately, a better method presented itself.

Gas-Powered Pump

Because the oxygen and hydrogen are supplied at high pressure to the unit, it seemed feasible to tap the high pressure for pump power. Use of the incoming oxygen flow, which would not vary during operation, can easily provide enough power to circulate the cooling water. A schematic of such a pump is shown in Figure 17.

In theory the pump worked. To see whether reality would cooperate a pump was built which was designed to operate at atmospheric pressure

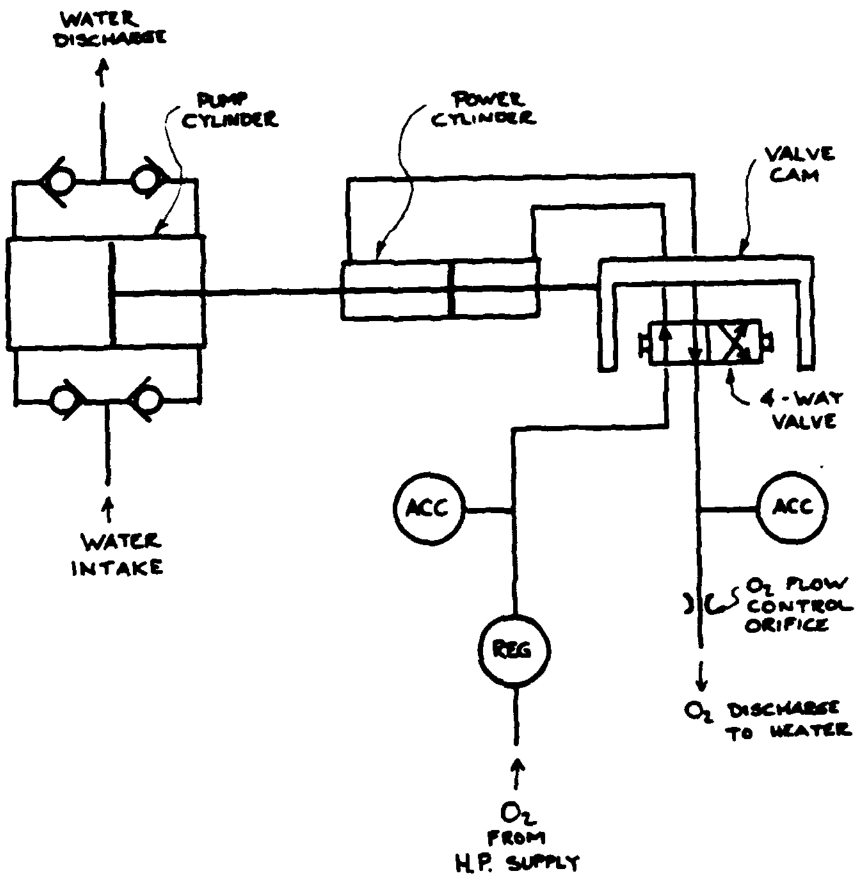


FIGURE 17. WATER PUMP SCHEMATIC

for demonstration purposes (Figure 18). It consists of two linked pneumatic cylinders. The smaller cylinder, 7/8-inch diameter, is the power source. The larger cylinder, 2-inch diameter, is the water pump. The power cylinder receives gas from the incoming oxygen line via a 4-way valve. The low-pressure side of the cylinder dumps back to the oxygen line. When a stroke has been completed, the 4-way valve is cammed to its reverse position, which switches pressure to opposite sides of the power cylinder, causing a continuous oscillating motion. Small accumulators located upstream and downstream of the power cylinder reduce pressure fluctuations in the oxygen line. A sample calculation of the sizes and pressures required for a unit to operate at 450 FSW is shown in the appendix of this report.

Speed of the pump is controlled by the rate at which the oxygen flows through a sonic orifice on its way to the heater, and by the pressure at which the gas flows through the power cylinder. Pressure drop across the power cylinder depends on the ratio of the areas of power and pumping cylinders and the pressure against which the water must be pumped, as well as friction.

The pump cylinder, continuously oscillating, draws water through alternate check valves, and discharges through two more alternate check valves. Water flow is continuous, except for a slight pause at the end of each stroke.

The breadboard prototype, although crude, demonstrated conclusively that the pumping method is feasible. The device could certainly be refined in future development to provide pumping in a very small package.

FUTURE DEVELOPMENT

The performance of the tube burner and the gas-powered water pump were sufficiently encouraging that we are confident that a package can be developed which can combine them in simple, reliable form. The resulting device would be small, simple, and would require no external electrical

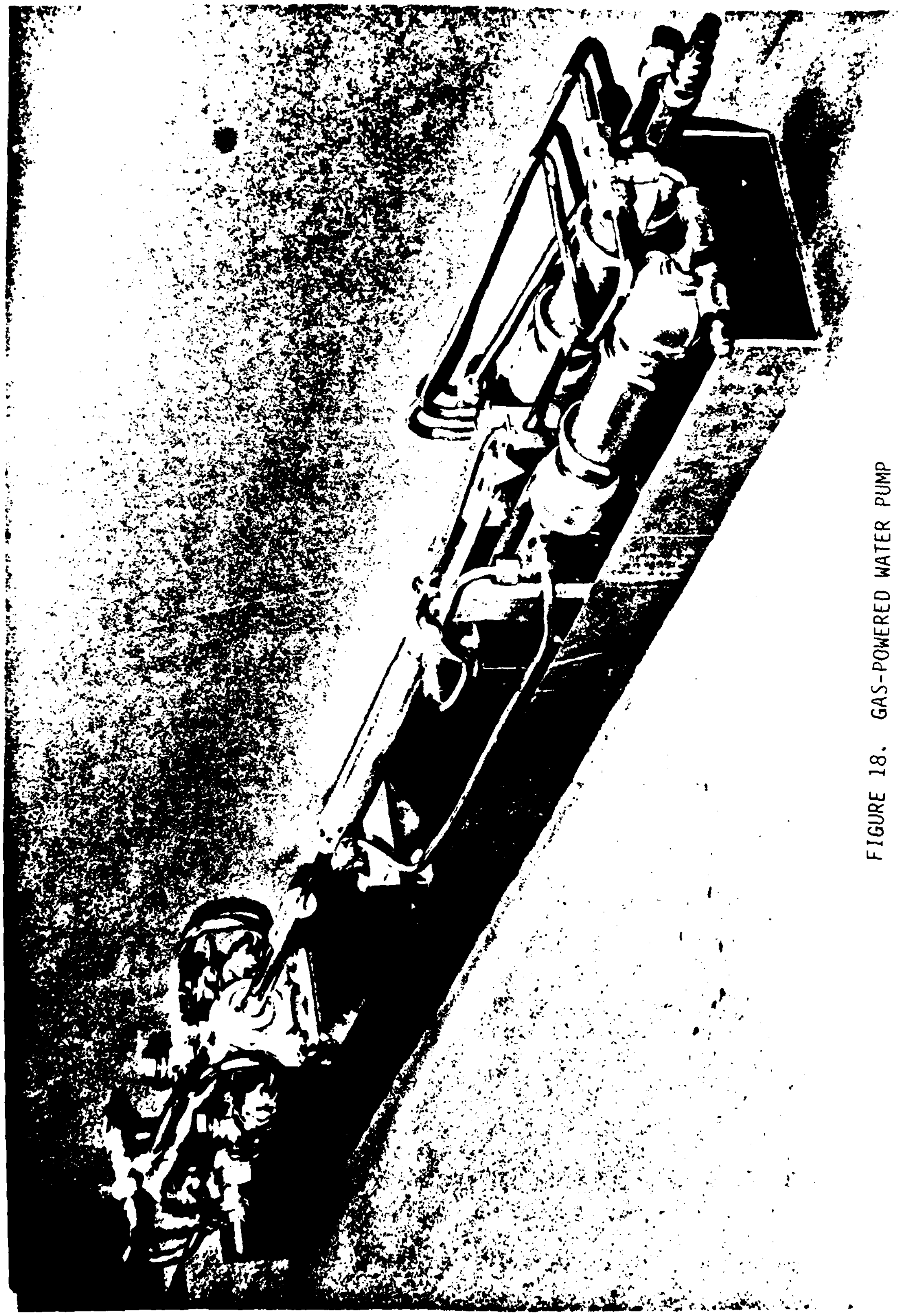


FIGURE 18. GAS-POWERED WATER PUMP

power source at any time, drawing all of its energy for pumping and heating the diver's hot water from combustion of the hydrogen.

Such a device could be used in places other than on the diver's back. It could, for instance, be used as a diver heater on a swimmer delivery vehicle, providing heat to all of the divers simultaneously and operating from a set of fuel bottles on the SDV. It could be used as a PTC heater, circulating hot water to convective radiators within the shell. Operating with a small amount of excess oxygen, combustion products would not be toxic and the excess oxygen would be consumed by the PTC occupants, reducing the amount supplied by the environmental control system of the PTC.

The only unsolved problem in operation is removal of the condensate. It normally drains out by gravity when burner orientation permits. If orientation should change, some means would have to be found to allow the condensate to drain. However, we do not consider this to be a difficult problem to solve.

The heater-pump's apparent potential for several uses makes it an attractive energy source for future Navy needs, and we hope that development of it will be continued.

APPENDIX

SAMPLE CALCULATION OF A GAS-POWERED WATER PUMP

SAMPLE CALCULATION OF A GAS-POWERED WATER PUMP

DESIRED WATER FLOW = 1 GPM @ 5 PSID

O_2 REQUIRED FOR COMBUSTION = 0.3 SCFM

- ASSUME A PUMP AS SHOWN SCHEMATICALLY IN FIG. 17

- ASSUME THAT THE O_2 PRESSURE IN THE PUMP IS ABOUT 500 PSIA, FOR NOW.

WE NOW HAVE:

ACTUAL WATER FLOW = 1 GPM = 231 IN^3/MIN

ACTUAL GAS FLOW $= 0.3\left(\frac{14.7}{500}\right)(1728) = 15.24$ IN^3/MIN

REQ'D $\left(\frac{\text{WATER PISTON}}{\text{GAS PISTON}}\right)$ AREA RATIO $= 231/15.24 = 15.16$

REQ'D DIAMETER RATIO $= \sqrt{15.16} = 3.89$

- ASSUME WATER PISTON DIA = 3" AREA = 7.069 IN^2

- ASSUME GAS PISTON $= 3/3.89 = .77$ USE $.75 = 3/4"$
  AREA = .442 IN^2

TO PUMP 1 GALLON OF WATER, THE PISTONS MUST MOVE:

$$231 / 7.069 = 32.7 \text{ IN}$$

- ASSUME A 5 IN. STROKE.
  THE PUMP WILL THEN MAKE $32.7/5 = 6.5 \frac{\text{STROKES}}{\text{MIN.}}$

REQUIRED FORCE ON WATER PISTON = 5 PSI (7.069 IN^2) = 35.3 LB

GAS ΔP REQUIRED TO PRODUCE 35.3 LB FORCE =

$$\frac{35.3 \text{ LB}}{.442 \text{ IN}^2} = 79.9 \text{ PSI}$$

WE THUS HAVE ABOUT 80 PSI OF GAS ΔP REQUIRED TO PRODUCE A 5 PSI WATER ΔP.

- ASSUME ANOTHER 20 PSI OF GAS ΔP FOR FRICTION, FOR TOTAL GAS ΔP OF 100 PSI

FINAL CALCULATIONS:

450 FSW = 215 PSIA

- FOR SONIC FLOW THROUGH O_2 FLOW CONTROL ORIFICE, THE POWER CYLINDER EXHAUST PRESSURE MUST BE AT LEAST $(215)(2) = 430$ PSIA
- SINCE WE HAVE 100 PSI REQUIRED TO DRIVE THE PUMP, THE POWER CYLINDER UPSTREAM PRESSURE = 530 PSIA

$$\text{ACTUAL GAS FLOW} = 0.3\left(\frac{14.7}{530}\right)(1728) = 14.38 \text{ IN}^3/\text{MIN}$$

$$\text{ACTUAL WATER FLOW} = 14.38\left(\frac{3}{3/4}\right)^2 = 230 \text{ IN}^3/\text{MIN} = .996 \text{ GPM}$$

$$\text{CYCLIC RATE} = \frac{230}{5 \times 7.069} = 6.5 \text{ STROKES/MIN}$$

FINAL PUMP CHARACTERISTICS:

POWER CYLINDER DIA = 3/4"

PUMP CYLINDER DIA = 3"

WATER FLOW = 1 GPM @ 5 PSID

GAS FLOW = 0.3 SCFM

GAS PRESSURE TO PUMP = 530 PSIA

GAS PRESSURE TO O_2 FLOW CONTROL ORIFICE = 430 PSIA

STROKE = 5"